한국해양공학회지 제22권 제1호, pp 6-12, 2008년 2월 (ISSN 1225-0767)

Mode Selection of Leaky Lamb Waves in Steel Plate

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KEY WORDS: Mode Selection, Leaky Lamb Waves, Steel Plate, Nondestructive Testing

ABSTRACT: *The dispersion and attenuation of Lamb and Leaky Lamb waves propagating in a 1 mm-thick steel plate were investigated. For acquiring a long (or large) range inspection capability, the fundamental symmetric and anti-symmetric wave modes (S0 and A0) over low frequencies were studied. Based on the dispersion curves, as well as pitch-catch and multi-mode simulations, it was shown that the S0 mode over low frequencies is the proper mode to minimize the dispersion and attenuation. In addition, it was shown that the S0 mode couldbe easily distinguished under multi-mode simulation since it has a larger group velocity than the A0 mode.*

1. Introduction

Lamb waves are guided waves which propagate in the plane of a plate and their interaction with anomalies or defects makes them useful for a certain inspection purpose. The plate guides the ultrasonic waves along the plate. That is why the plate is called a waveguide and the ultrasonic waves are called ultrasonic guided waves. With the guidance, the ultrasonic guided waves propagate in the plane of a plate and the absorption of energy waves is mainly dependent on the material damping. If the plate has very little damping, the energy of waves is practically not absorbed as they propagate; hence, they can travel over a long distance.

Two types of Lamb wave modes exist: symmetric and anti-symmetric. The symmetric wave modes are symmetric with respect to the mid-plane of plate. Anti-symmetric wave modes are anti-symmetric with respect to the mid-plane of the plate. In general, the number of modes increases with the frequency. Therefore, an infinite number of symmetric or anti-symmetric wave modes can exist. For each of these modes, their velocity (phase or group) varies with frequency, which means that they are all dispersive. The effect of dispersion on a propagating wave packet of acoustic energy is that the energy spreads in time and space as it propagates. Hence, close to a source, the signal is similar to an input, but as the distance increases, the signal duration increases and the peak amplitude decreases. Both of these features are undesirable in an inspection application as the sensitivity decreases, and as reflections from two artifacts in close proximity might not be separated and identified. The use of Lamb wave is then not as straight-forward as the use for bulk waves such as P (primary) and S (secondary) waves. Hence, the dispersion is a key factor, and modes with low dispersion has to be selected and the signal to noise ratio needs to be as high as possible to maximize the range of inspection. The selection of a suitable Lamb wave mode is fundamental for the guided waves-based nondestructive testing for a long-range inspection.

Another important effect is the attenuation. Attenuation is primarily due to leakage of energy into surrounding fluid in any test structures which contain fluid or are immersed in fluid. Therefore, it is very likely that this reduces the choice of a suitable leaky Lamb wave mode. Thus, the mode satisfying the following criteria should be selected for ultrasonic guided waves-based nondestructive testing: (1) it is not very dispersive, the resolution is not worsen as the signal duration increases and the peak amplitude of the signal does not decrease as it propagates. (2) it has very low attenuation when the plate is in contact with a fluid.

Most works related to the ultrasonic guided waves-based nondestructive testing have investigated the mode selection. A careful mode selection for a specific inspection purpose should be carried out (Wilcox et al., 2001; Pan et al., 1999). Relatively much works on the mode selection have been done for cylindrical structures. For the mode selection, in general, fundamental cylindrical guided (or Lamb) wave modes such as longitudinal L(0,1), torsional T(0,1), and flexural F(1,1) modes have been considered to be important (Na et al., 2005) However, other modes have been also carefully investigated for a particular application. It is shown that the second longitudinal wave mode L(0,2) at a frequency of about 70kHz

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is attractive for a specific transducer system used to inspect chemical plant pipework (Alleyne and Cawley, 1996). Kwun et al. (2004) chose torsional wave modes because it almost dispersion free to the presence of liquid in the pipe. Other studies also show that modes should be selected for specific inspection purposes (Guo and Kundu, 2001; Na and Kundu, 2002; Pan et al., 1999). However, the mode selection for Lamb (or plate) waves has not been much emphasized although there are an excellent works done by Diligent (2003) and Alleyne (1991). The reason is that at low frequency only two fundamental Lamb wave modes S0 (symmetric) and A0 (anti-symmetric) exist. Thus, those modes have been selected for ultrasonic guided-wave-based tests at low frequency ranges. However, those modes are not good for all situations because the mode selection depends not only on inspection quality but also on long-range inspection capability. In other words, the selection of a particular mode should count on its sensitivity to the defects, which are sought and its ability to travel over long distances without significant energy loss (Rose et al., 1994). Therefore, the selection is quite situation oriented procedure.

Then, how we should choose the proper mode for a certain inspection purpose is the arising question. It can be done by investigating velocity and attenuation dispersion curves. From the dispersion curves, we can figure out how a certain wave mode disperses and attenuates. The calculation of the dispersion curves can be numerically done (Na et al., 2005). In addition to the dispersion curves, numerical simulation of the guided waves excitation and reception can confirm the mode selection. Thus, it is significant to investigate the dispersion curves and numerical simulation. This paper introduces a mode selection of leaky Lamb waves in a steel plate for a long-range inspection. The selection procedure was illustrated by investigating dispersion curves and numerical simulations. For the investigation, three types of dispersion curves (phase velocity, group velocity and attenuation) were numerically calculated, and pitch-catch and multi-mode simulations were carried out. This study helps people make a proper mode selection for the Lamb waves-based inspections.

2. Wave Propagation Model in Flat Plate

In order to construct the wave propagation model, we first determine the nature of the bulk waves which can exist in isotropic materials. Once the nature of the bulk waves is known, the stresses and displacements in a layer can be expressed in terms of the amplitudes of all of the bulk waves that can exist in that layer. The stresses and displacements at the boundaries of each layer can be combined with the boundary conditions to describe the entire system in one large global matrix that relates the bulk wave amplitudes to the physical constraints (Pavlakovic et al., 1997). Figure 1 shows the construction of a five-layer flat plate system. The partial (or bulk) waves labeled L+-, SV+-, and SH+- are assembled by matching the boundary conditions at each of the interfaces (Lowe, 1995). Here, L, SV, and SH stand for longitudinal waves (P waves), shear vertical waves, and shear horizontal waves. In addition, + denotes the downward direction, and the - denotes the upward direction of the plate case.

The SH+- partial waves are omitted in the case of Lamb waves in an isotropic plate, leaving just 4 partial waves in each layer. The L+- and SV+- partial waves are omitted in the case of Love waves in an isotropic plate, leaving just two partial waves in each layer. At certain frequency and wave number and attenuation combinations, these partial wave combine to form a guide wave which propagates down the axis of the infinitely long plate. These valid combinations may be found by solving the global matrix equation for its modal response. For a given system, the global matrix equation is a function of frequency (time varying component), real wave number (spatially varying component), and attenuation (spatial decay rate). Solutions must be found iteratively by varying these three parameters until a valid root is converged upon. Once an initial root has been found, roots that lie on the same line of solutions, or dispersion curve, can be traced. This process can be repeated to find other dispersion curves that exist. Once all the dispersion curves have been traced, we can extract information about the guided waves and determine which are promising for characterizing the system.

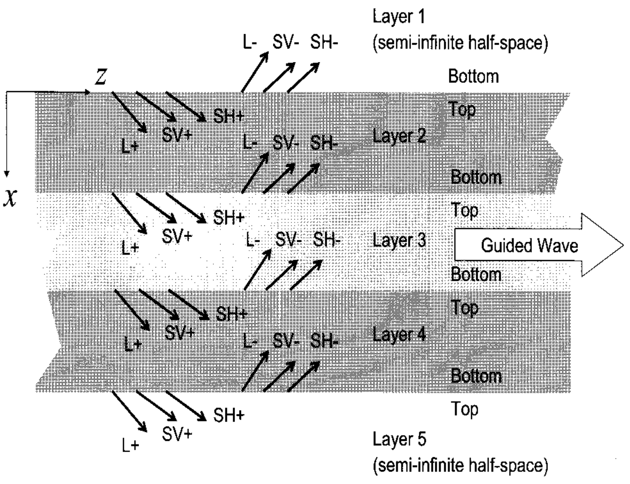
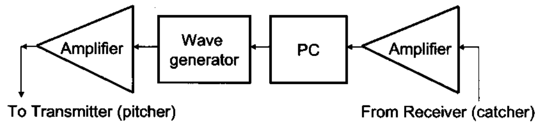
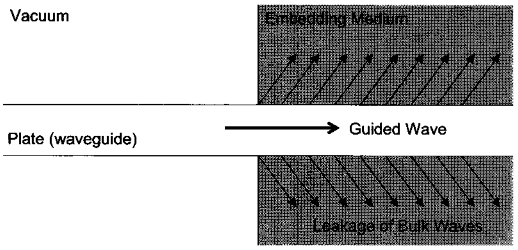


Fig. 1 Geometry of a five-layer flat plate system showing the partial waves in each layer (L+-, SV+-. SH+-) that combine to produce a guided wave



(a) Pitch and Catch Mode



(b) Lamb Wave Attenuation

Fig. 2 A pitch and catch mode for ultrasonic guided wave testing (a) and Schematic of the Lamb wave attenuation due to the leakage of bulk waves into the medium surrounding the waveguide (b)

Figure 2 shows a pitch and catch mode for ultrasonic guided wave testing and Schematic of the Lamb wave attenuation due to the leakage of bulk waves into the medium surrounding the waveguide. If the plate is surrounded by vacuum (most likely air) the main attenuation is due to the material damping of the plate. However, once the plate is embedded by medium such as fluid or solid the leakage of bulk waves occurs.

3. Lamb Waves Simulation

Figures 3 and 4 show the phase and group velocity dispersion curves for a 1mm thick steel plate. The phase velocity dispersion curves (phase velocity against frequency) display the rate at which an individual crest of the wave travels. The group velocity dispersion curves (group velocity against frequency) show the speed at which a guided wave packet travels. For isotropic non-attenuative media, this can also be seen as the velocity of the energy of the wave. Under the situation that attenuation should be considered, the attenuation (decay of the guided wave) as a function of frequency is further representation of the dispersion curves.

Two types of Lamb modes exist: there are symmetric denoted by solid lines and anti-symmetric denoted by dashed lines as shown in Figs. 3 and 4. The symmetric modes are denoted by Si, where i is the order of the mode and anti-symmetric modes are denoted by Ai. It can be shown from Fig. 3 and Fig. 4 that the number of modes increases with the frequency. Thus, an infinite number of symmetric and anti-symmetric modes can exist. For each of those modes, their velocity varies with frequency, which means that they are all dispersive. The effect of dispersion on a propagating wave packet of acoustic energy is that the energy spreads in time and space as it propagates. Hence, close to the source, the signal is similar to the input, but as the distance increases, the signal duration increases and the peak amplitude decreases. However, if a proper mode at a specific frequency is selected, the dispersion pattern is not significant. For example, Figs. 5 and 6 show the received S0 and A0 modes at distances (100, 500, and 1000mm) from the excitation point. The frequency of the carrier wave is fixed to 0.5MHz. In S0 mode, the dispersion is quite less than A0 mode; hence, A0 mode is not a proper mode because of the dispersive pattern. However, if the frequency increased to 2.0MHz, then the S0 mode has also severe dispersion as shown in Fig. 7. The dispersion is the key factor and the modes with low dispersion have to be chosen. The fundamental symmetric mode S0 at a low frequency satisfies the criteria.

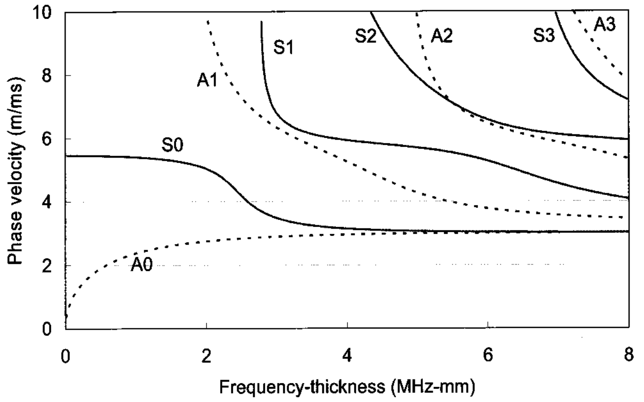


Fig. 3 Phase velocity dispersion curves of 1mm-thick steel plate in air

In reality, only one mode, say S0, does not usually propagate. Multiple wave modes can be generated in the steel plate. Depending on the frequency of the carrier wave, several wave modes can be superposed. Figure 8 shows the pitch-catch multi-mode simulation for 1mm-thick steel plate in air. The pitch-catch assumes a configuration of two transducers at separate positions along the plate as shown in Fig. 2(a). Here, we fixed the distance between transducers to 100 mm. As shown in Fig. 8, as frequency increases more modes are superposed. Thus, in NDT application, time domain is usually converted into frequency domain or time-frequency domain using short-time Fourier transform or Wavelet transform (Na et al., 2006). Those domains help ones to analyze the signals. However, at a low frequency, only one other Lamb mode is present: the fundamental anti-symmetric mode A0. The first two figures of Fig. 8 represent the case.

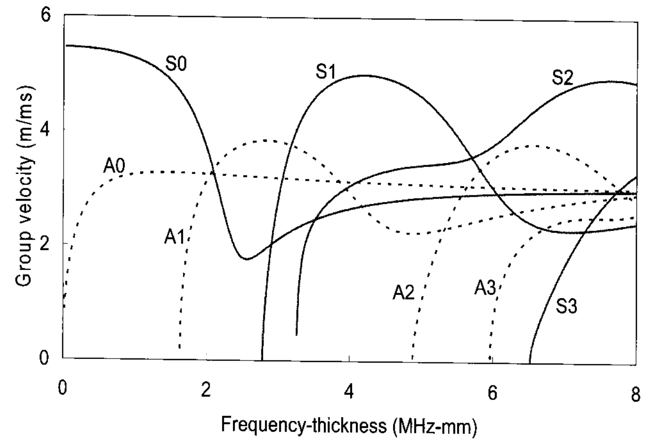


Fig. 4 Group velocity dispersion curves of 1mm-thick steel plate in air

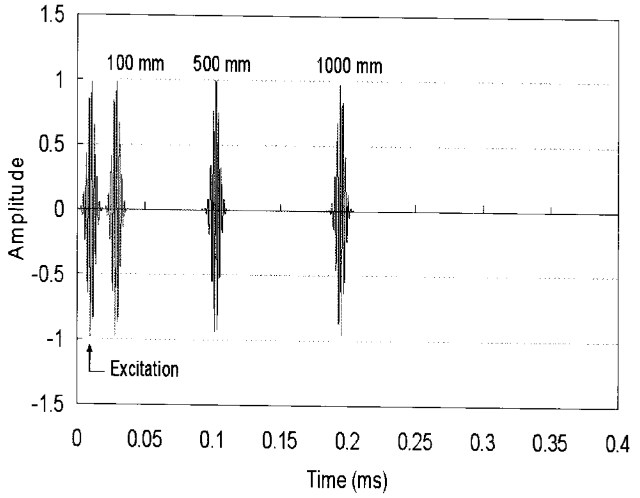


Fig. 5 S0 Lamb wave mode at distances (100, 500, and 1000mm) from the excitation point. The frequency is 0.5MHz

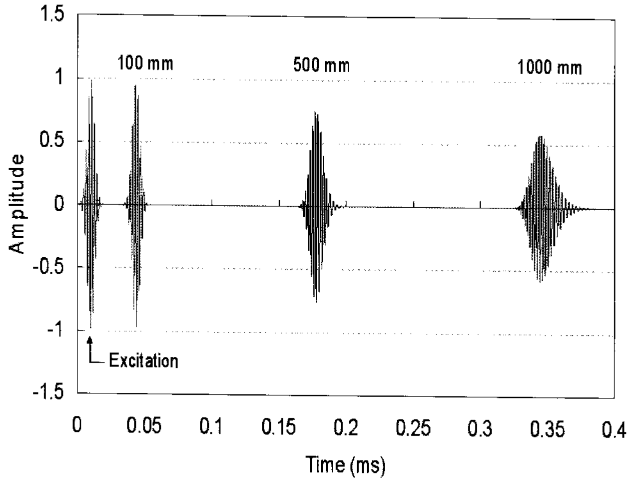


Fig. 6 A0 Lamb wave mode at distances (100, 500, and 1000mm) from the excitation point. The frequency is

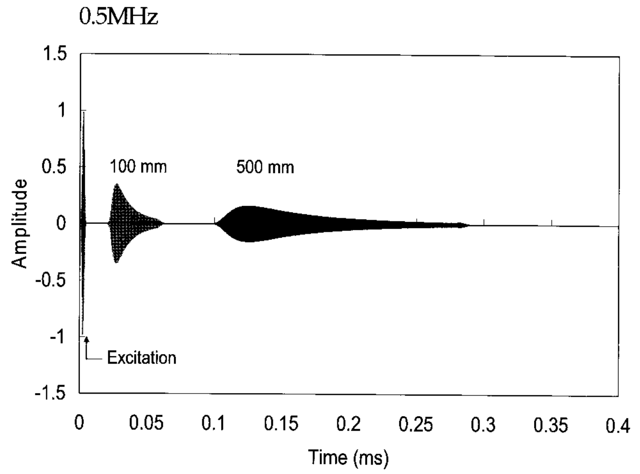


Fig. 7 S0 Lamb wave mode at distances (100 and 500mm) from the excitation point. The frequency is 2.0MHz

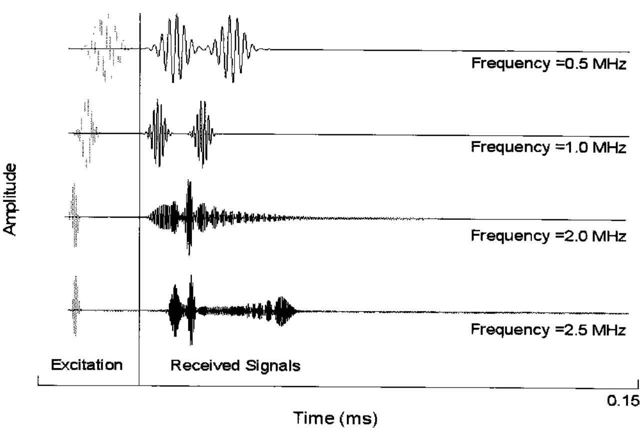


Fig. 8 Pitch-catch multi-mode simulation for 1mm-thick steel plate in air

4. Leaky Lamb Waves Simulation

For this study, leaky Lamb waves refer to the guided waves that exist in a single elastic, isotropic layer that is immersed in surrounding water. To investigate the acoustic properties of the leaky Lamb waves, the phase and group velocity dispersion curves of 1mm-thick steel plate in water are obtained as shown in Fig. 9 and Fig. 10. In comparison to the velocity dispersion curves of Lamb waves, Fig. 9 and Fig. 10 show an additional wave mode called the Stoneley-Scholte wave, also called the Scholte wave. This wave propagates at the boundary between a fluid and a solid, and it has proved to be a useful tool in non-destructive testing or in marine seismology (Favretto-Anrès and Rabau, 1997). However, this wave is not a Lamb wave; hence, no more investigation was carried out on it.

In this leaky system, as the wave propagates down the isotropic layer, bulk waves are generated in the surrounding water layers. These bulk waves carry energy away from the system and cause attenuation. In general, attenuation is primarily due to leakage of energy into surrounding fluid (or solid) in any test structures which contain fluid or are in contact with fluid (or solid). Hence, it reduces the choice of a suitable Lamb mode to those who have very little out-of-plane displacement at the contacting surface of the plate. The fundamental S0 Lamb mode over low frequencies satisfies such criteria because of the following reasons. First, this mode is not very attenuable as shown in Fig. 11. Second, the resolution is not worsen as the signal duration increases and the peak amplitude of the signal does not decrease as it propagates, as shown in Fig. 12, which shows the S0 modes at the different catching points (10, 50, and 100mm) in pitch-catch mode simulation. In the case of A0 mode, the peak amplitude of the signal decreases as it propagates as shown in Fig. 13. Thus, the S0 mode has very low attenuation over low frequencies; and the signal to noise ratio does not change. These make it a suitable mode for NDT.

Figure 14 shows the pitch-catch multi-mode simulation for 1mm-thick steel plate in water. In a leaky system, at a low frequency, S0 and A0 modes and Scholte wave are major contribution of the superposition. First two figures of Fig. 14 represent this superposition. Since the group velocity of S0 mode is larger than those of A0 mode and Scholte wave at a low frequency as shown in Fig. 10, we can easily distinguish the signal representing S0 mode. The use of S0 mode at a low frequency can overcome the obstacles caused by dispersion and attenuation; hence, it can be a proper candidate for a certain purpose of nondestructive testing.

Another investigation was carried out to support S0 mode as shown in Fig. 15 and Fig. 16. Figure 15 shows displacements of S0 mode at frequency of 1MHz while Fig. 16 shows displacement of A0 mode at the same frequency. Here, UX denotes the displacement in the direction normal to the layer (x), UZ denotes the displacement in the direction of propagation of the wave (z), and UY indicates the displacement in the direction normal to the plane of calculation (y). The shadow plane in the figures represents the plane of calculation. Thus, UZ is the in-plane displacement and others are out-of-plane displacements. Especially, UX is the out-of-plane displacement at the contacting surface of the plate with water. At the top and bottom surfaces, the absolute values of S0 and A0 modes are 0.28 and 1.26 nm, respectively. The displacement of A0 is almost 4.5 times as S0. That means the leakage of energy of A0 mode into surrounding water is much more than S0.

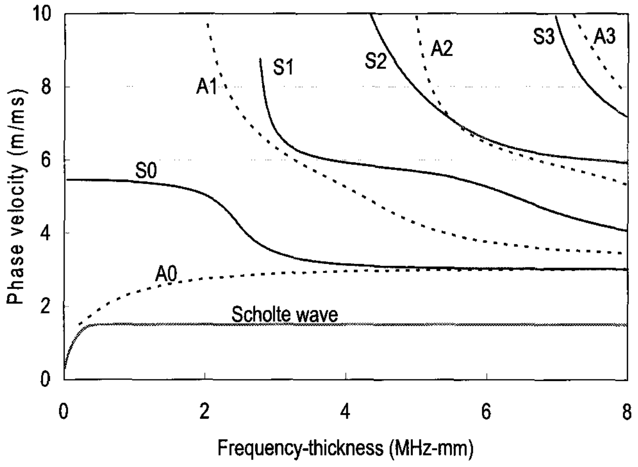


Fig. 9 Phase velocity dispersion curves of 1 mm-thick steel plate in water

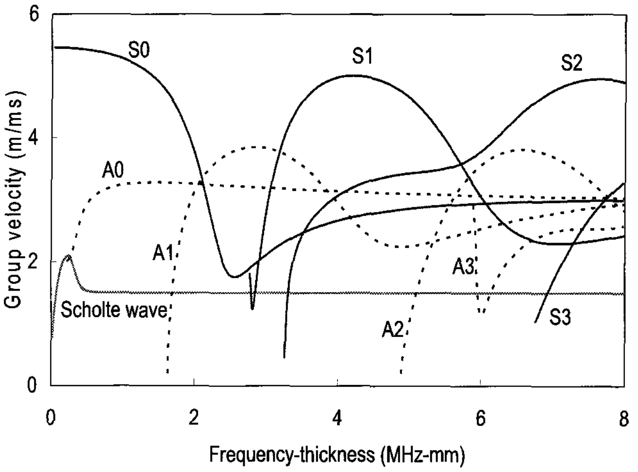


Fig. 10 Group velocity dispersion curves of 1mm-thick steel plate in water

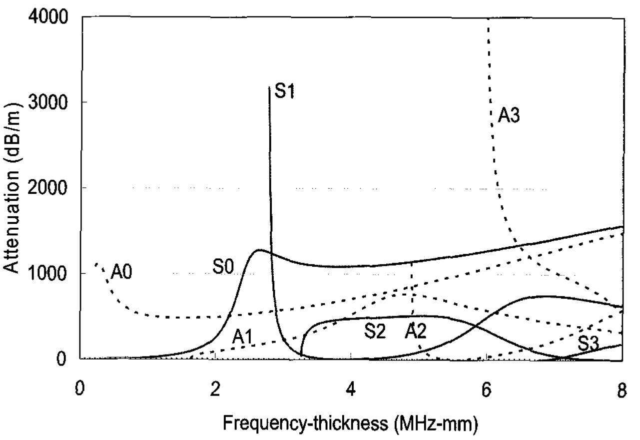


Fig. 11 Attenuation dispersion curves of 1mm-thick steel plate in water

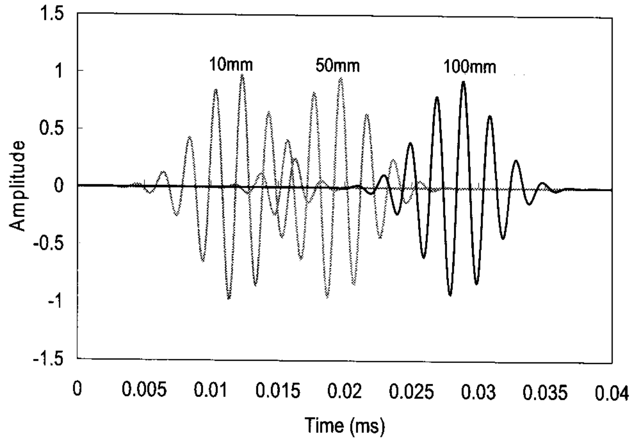


Fig. 12 S0 wave modes in pitch-catch mode simulation

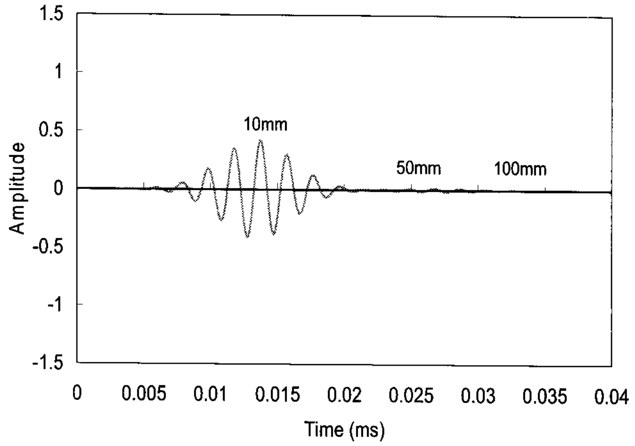


Fig. 13 A0 wave modes in pitch-catch mode simulation

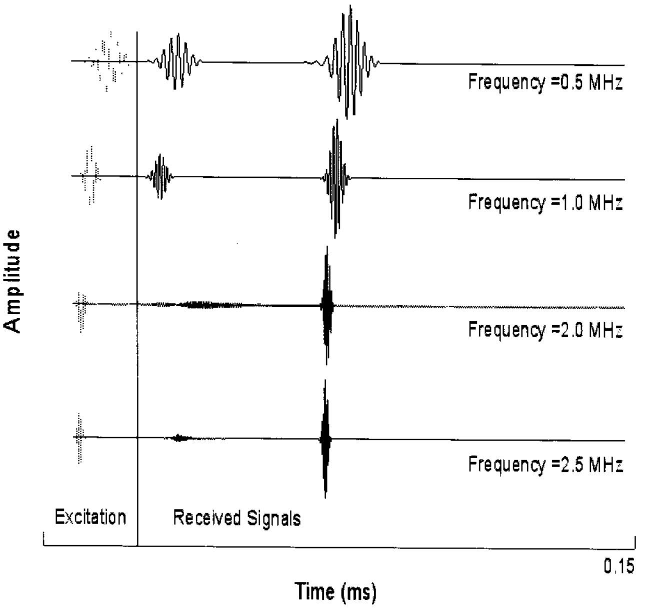


Fig. 14 Pitch-catch multi-mode simulation for 1mm-thick steel plate in water

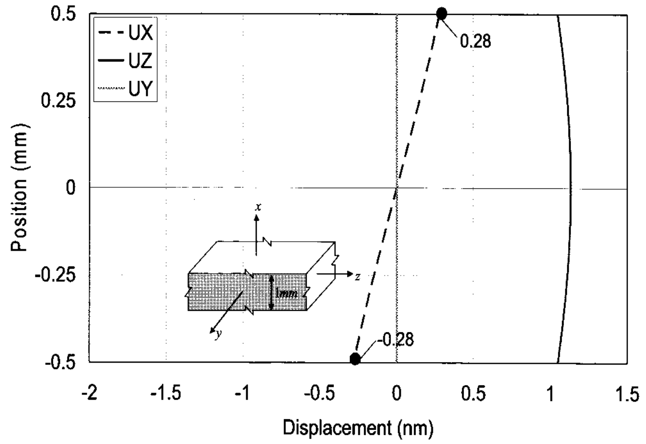


Fig. 15 Displacements of S0 mode at frequency of 1MHz

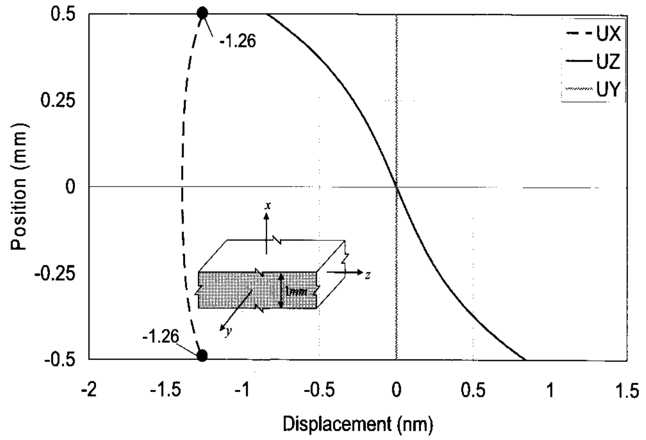


Fig. 16 Displacements of A0 mode at frequency of 1MHz

5. Summary and Conclusion

Dispersion and attenuation of Lamb and leaky Lamb wave propagating in 1mm-thick steel plate were numerically investigated by the dispersion curves and the pitch-catch and multi mode simulations. In addition, the displacements of S0 and A0 mode at frequency of 1MHz were obtained to see the values of out-of-plane displacements. Especially, the out-of-plane displacements (UX) at the contacting surface of the plate with water were carefully studied.

It is shown that the fundamental symmetric Lamb wave mode (S0) over low frequencies is a proper mode selection for acquiring a long range inspection capability. The use of S0 mode over low frequencies minimizes dispersion and attenuation due to the following facts.

(1) S0 mode has less attenuation, which means that it has very little out-of-plane displacement at the contacting surface of the plate, so less acoustic energy goes away from the system.

(2) S0 mode is less dispersive, so the resolution is not worsen as the signal duration increases and the peak amplitude of the signal does not decrease as it propagates.

(3) S0 mode can be easily distinguished under multi-mode simulation since it has larger group velocity over A0 mode. Thus, it causes a less signal analysis procedure.

(4) UX of A0 mode is almost 4.5 times as S0, which means the leakage of energy of A0 mode into the surrounding water is much more than S0.

The numerical demonstration gives the idea how the mode selection should be made. However, it should be noted that this choice is made solely based on the dispersion and attenuation of leaky lamb wave propagating in the thin steel plate. Its sensitivity to anomaly and generation is an other issue.

Acknowledgement

This work was financially supported by Port Remodeling Project under Ministry of Maritime Affairs and Fisheries in 2007.

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2007년 7월 30일 원고 접수
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